The soft multi-legged robot inspired by octopus

-Climbing various columnar objects-

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Abstract

In this paper, we develop a soft climbing robot made of silicone. Octopus-like behaviour is realized by a simple mechanism utilizing the dynamics of the soft body, and the robot can grasp various objects of unknown shape. In addition, by inching its truck, it can climb various columnar objects. Experiments using pipes, long balloons, and natural trees are conducted to evaluate the effectiveness of the proposed robot.

Keywords: Soft robot, Multi-legged robot, Bioinspired robot, Octopus-like robot

1. Introduction

In recent years, robots operating in real complex environments such as rescue operation, inspection and maintenance of huge structures, and agriculture and farming, have attracted considerable attention [1-2]. However, conventional robots are designed to operate in known simple environments such as industrial factories, and it is difficult to design them to operate in unknown complex environments. In general, to operate in complex environments, many degrees of freedom are required and, in addition, it requires complex controllers to move them. However, the computational cost for the controller increases exponentially with the number of degrees of freedom. Hence, real-time processing becomes impossible.

However, natural creatures, such as insects or lower animals, can behave skilfully in real complex environments despite their small brain. They utilize interaction between their bodies and environment to realize skilful behaviours, which reduces the computational cost in the brain. In other words, the dynamics of the body conduct necessary calculation to control the body, instead of the brain. This approach is the focus of various research areas such as morphological computation, dynamic based control, and affordance. Recently, it has been applied to robot design.

Soft robotics is one of the most powerful approaches to realizing such robots. By realizing the body using soft material, a robot can utilize various dynamical properties by interacting with its environment. Thus, various soft robots have been proposed [3-10, 14]. However, these conventional soft robots were very simple, and only simple grasping behaviour or simple locomotion on horizontal plane was realized.

To improve the performance and to add another functions to soft robots, we focus on octopi. In conventional studies, some octopus-like robot have been developed [15-16]. However, to realize octopus-like behaviour, the mechanism of these octopus-like robots become more complex than usual soft robots. We also developed a climbing robot TAOYAKA that utilises octopus-like behaviour to grasp various pillars [13]. However, the robot was composed of many aluminium parts, and the size of the robot was big and its mechanism was very complex.

Therefore, to realize a small multifunctional soft robot with simple mechanism is a big challenge in this research field.

In our previous works, to tackle this problem, we developed a soft manipulator that reproduce octopus-like behaviour by employing just simple pulling mechanism [12, 17], and we demonstrated the advantage of the pulling mechanism than conventional mechanisms using air pressure [17].

In this paper, we propose and develop a small soft climbing robot by combining and improving our previous manipulator [17] and previous climbing robot [13]. Almost all the parts of proposed robot are made of silicon and driven by strings. Although the mechanism is very simple, this robot can grasp various object by utilizing octopus-like behaviour and, in addition, by inching its truck, it can climb various columnar objects. In summarize, the advantages of the proposed robot than conventional robots are

1. Realising octopus-like grasping behaviour by a simple mechanism using the dynamics of the soft body
2. Implementation of necessary mechanisms for climbing into small soft body
3. Simple control of the soft body with many degrees of freedom by utilising interaction with environment.
4. High adaptation ability to unknown columnar objects without sensing or heavy calculation

Experiments using pipes, long balloons, and natural trees are conducted, and we demonstrate the effectiveness of the proposed robot.

2. Relative works

2.1. Octopus-like flexible manipulator

It is reported that an octopus usually contacts its legs to an object from the root to the tip, as shown in Figure 1. By this strategy, an octopus always can grasp or cover an unknown object without sensing its shape [10-12]. This is the typical example to show the effectiveness of the control using dynamics of its body. In this paper, we propose a very simple soft leg mechanism that realize this octopus behaviour by utilizing the dynamics of the soft leg.

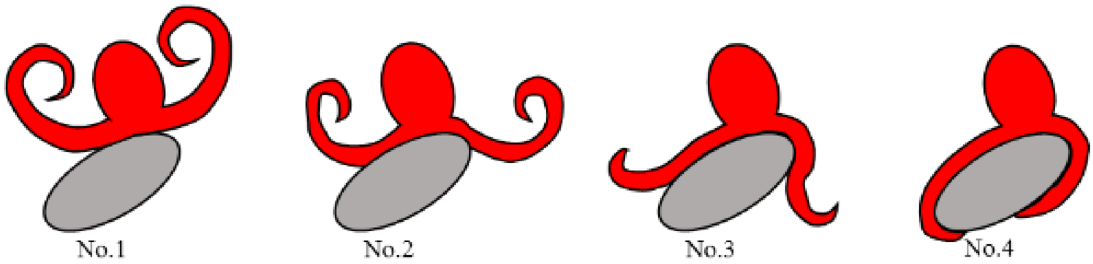

Figure 1 Grasping behaviour of octopus

2.2. TAOYAKA

In our previous work, we developed a six-legged robot inspired by an octopus [13]. Figure 2 shows the developed robot TAOYAKA. The leg is realized by six rigid links that are connected via passive joints. To realize octopus-like behaviour, rubber belts are utilized. Although this mechanism is effective for climbing large columnar objects, the mechanism is complex and reducing its size is very difficult. In this paper, we propose a new simple mechanism to realize octopus-like behaviour by utilizing the technique of soft robotics.

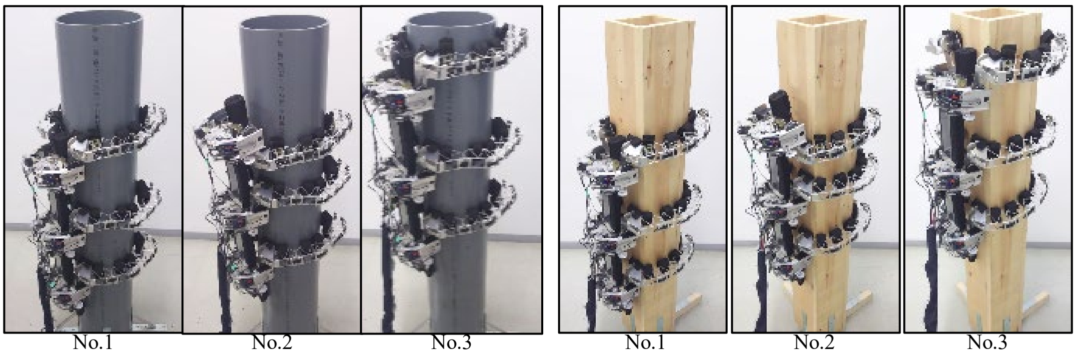

Figure 2 Climbing columnar objects

3. Developed Robot

Figure 3-4 shows the developed robot: TAOYAKA-S II. It has eight flexible legs, and its trunk is composed of three flexible links. To shrink the legs and the trunk, plastic strings are employed and the strings are connected to the motors through the polytetrafluoroethylene (PTEF) tubes. The motors are controlled by the PC, and the robot is driven by pulling the strings using the motors. Table 1 shows the comparison between the proposed robot and the previous robot (TAOYAKA III [13]). The size and the weight of the proposed robot is about one third of the previous robot.

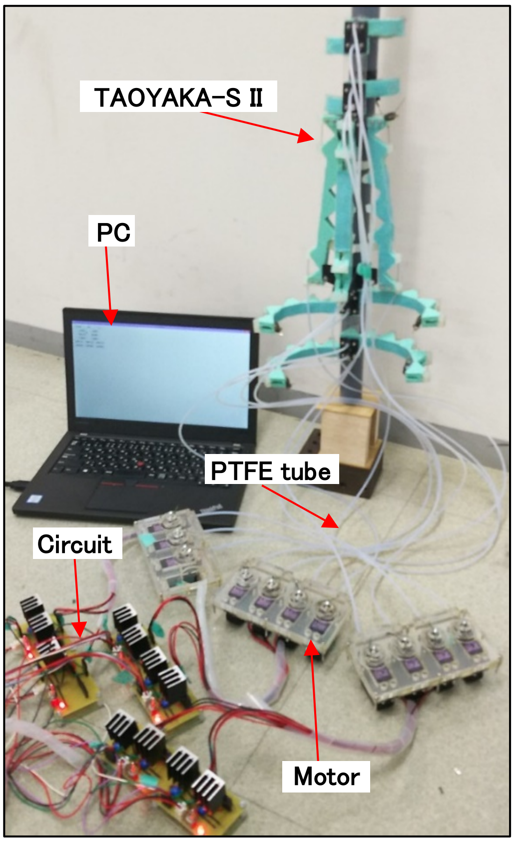

Figure 3 Developed robot

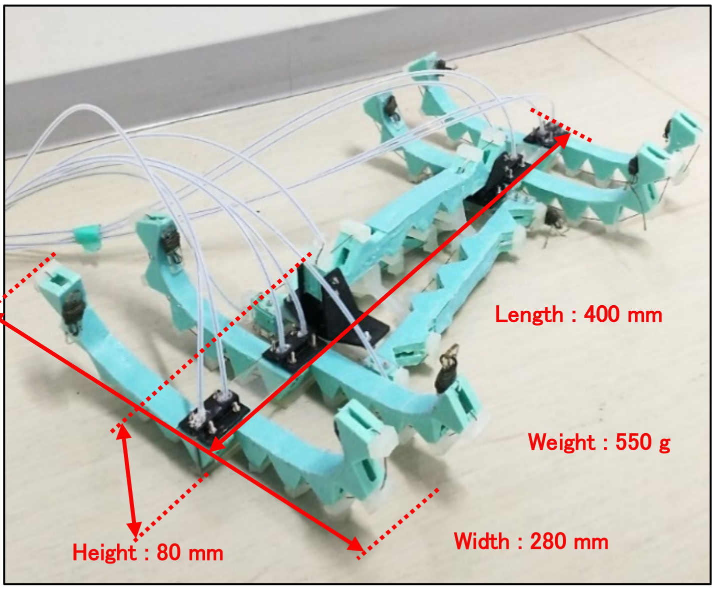

Figure 4 TAOYAKA-S II

TABLE. 1 Comparison of the proposed robot with TAOYAKA III

	Proposed robot	TAOYAKA III
Length	400 mm	720 mm
Width	280 mm	990 mm
Hight	80 mm	130 mm
Weight	0.55 Kg	1.8 Kg

3.1. Flexible leg

Figure 5 shows the developed flexible leg. It is composed of six segments which are made of silicon 60A, and a plastic string to close the leg is installed through the low friction PTEF tubes. To realize enough friction between objects and the leg, soft silicone blokes (30A) are attached on the inside of the leg. To prevent stretching the leg, a ribbon is attached to the outside of the leg.

To realize octopus-like grasping behaviour, we designed the initial shape of the leg as a part of a spiral as shown in Figure 6. By employing spiral shape, joint angle between segments increase gradually from the root to the tip as shown in Figure 5 and 6. Thus, the necessary force to close the joint increases as well, as shown in Figure 7, where we approximated the silicon rubber joint as a liner spring, and the force is proportional to rotation angle.

Owing to this physical property, by simply puling the string, the leg gradually closes from the root to the tip, and the octopus-like grasping behaviour described in section II is realized by this simple mechanism (Figure 8).

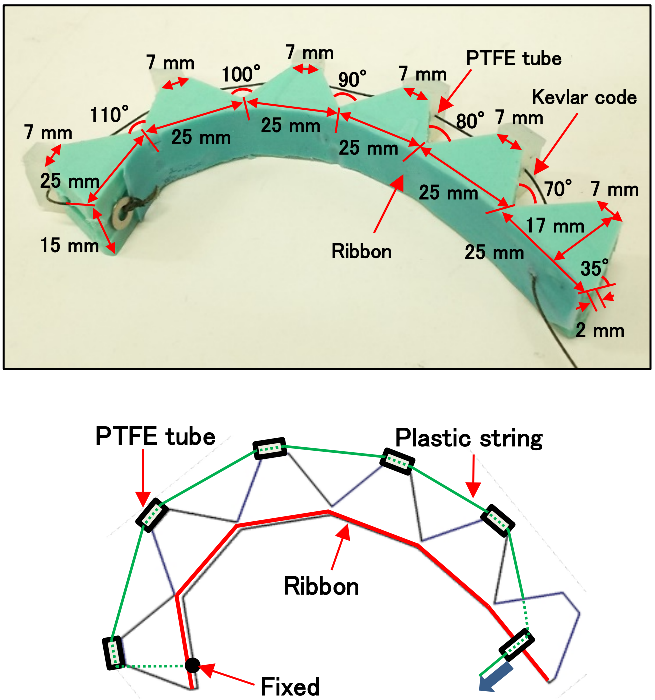

Figure 5 The developed flexible leg

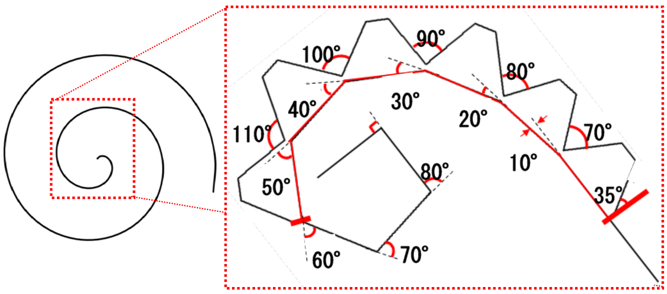

Figure 6 The initial shape of the leg

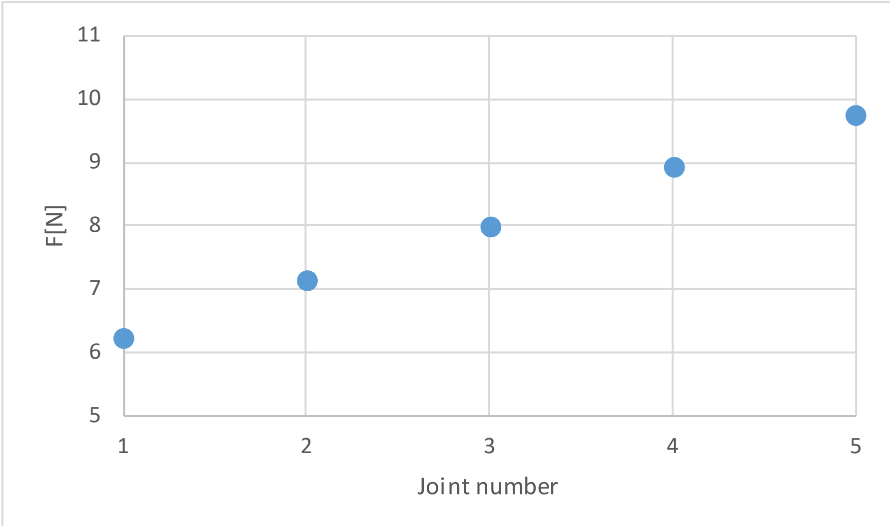

Figure 7 Pulling force of the string to close each joint

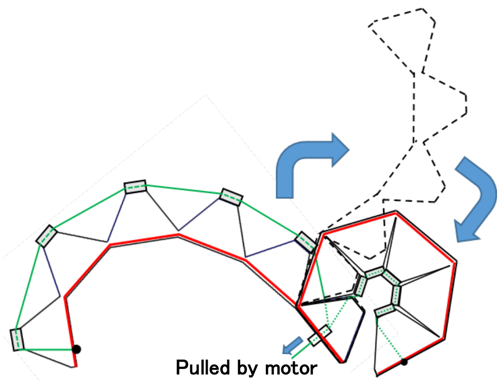

Figure 8 Movement of the flexible leg

3.2. Trunk

Figure 10 shows the developed trunk. The trunk is composed of three flexible links. By shrinking the links, the robot can realize inching motion to the desired 3-dimensional direction. The trunk is also made of silicon 60A and ribbons to reinforce the flexible links attached, as shown in Figure 9. To shrink the flexible links, a similar string mechanism is employed, as shown in Figure 11.

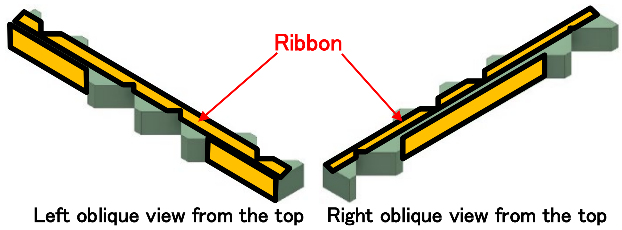

Figure 9 Flexible link for trunk

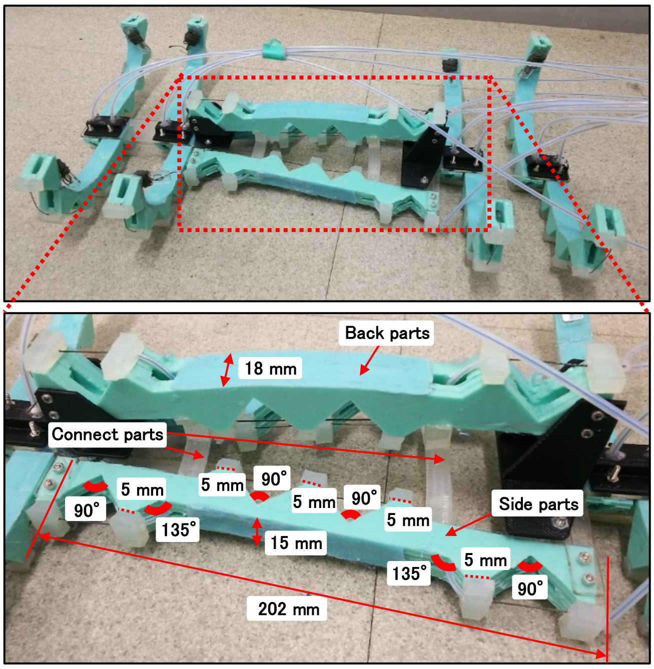

Figure 10 Developed trunk

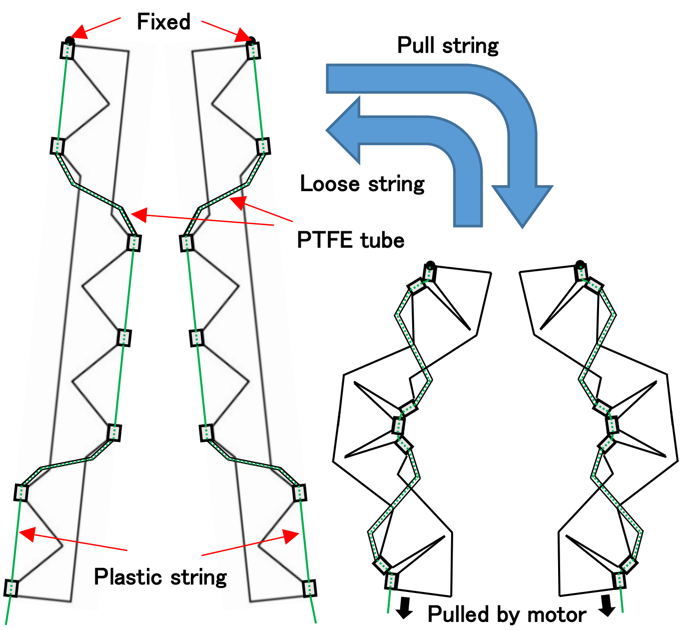

Figure 11 Movement of the trunk

3.3. Actuator

The legs and trunk are driven by pulling the strings. We employ 11 motors to pull the strings. We employ Tower Pro MG996R as the motors, and we modified it to endless rotation. Table 2 shows its specification. To reduce the weight of the robot, we put the motor outside of the robot. Figure 12 shows the pulling mechanism of the string. The string is connected to the motor through the PTFE tube. By rotating the motor, the pulley on the motor pulls the string. The motor is controlled by a PC via a motor driver circuit. To set a limit of the maximum pulling force, we set a limit of the electrical current for the motor driver.

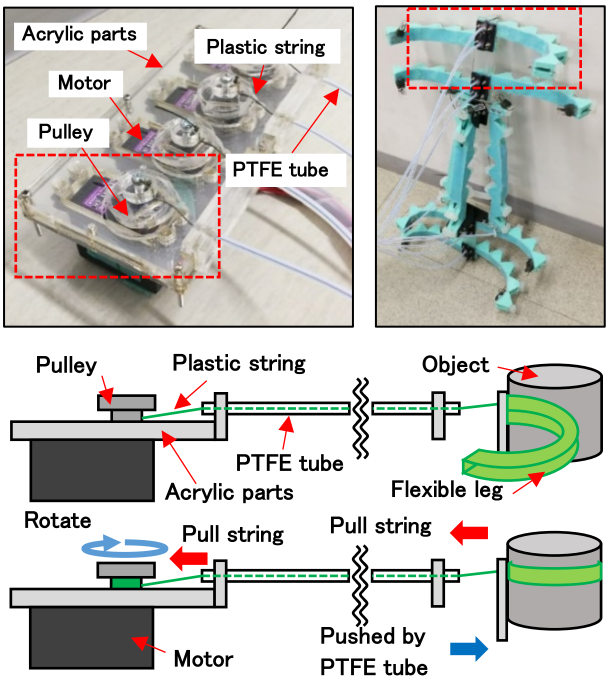

Figure 12 Robot constitution

TABLE. 2 Specification of the motor Tower Pro MG996R

Weight	55 g
Dimension	40.7×19.7×42.9 mm
Stall torque	9.4kg/cm (4.8v), 11kg/cm (6.0v)
Operating speed	0.19 s/60deg (4.8v), 0.15 s/60deg (6.0v)
Operating voltage	4.8~ 6.6v

3.4. Control

The main advantage of the proposed robot is the high-adaptability in unknown environments, by utilizing its octopus-like behaviour. This is realized passively by utilizing the dynamics of the soft body. Thus, the need to measure the environment or obtain complex feedback control becomes unnecessary; as a substitute, we employ a preprogramed simple pattern for climbing. Figure 13 shows the timing chart. Using this pattern, the robot repeats its inching motion by changing the grasping point.

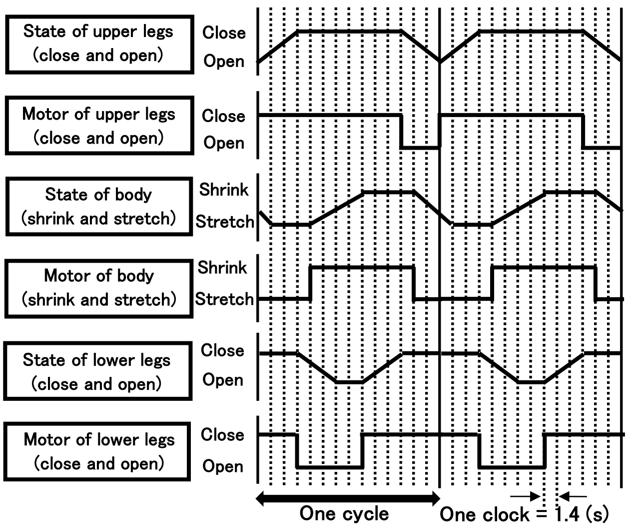

Figure 13 Timing chart

4. Experiment

To confirm the effectiveness of the developed robot, we conducted experiments using various columnar objects.

4.1. Experiments to confirm octopus-like behaviour

Figure 14 shows an example of the realized grasping behaviour. From the results, we confirmed that the octopus-like behaviour is realized by the proposed mechanism, and the leg contacts the objects from the root to the tip. In this experiment, the shape of the object was unknown and not measured. Nevertheless, the leg can grasp the object by just puling the string, and sensing or feedback control was not required. This is a major advantage of the proposed robot.

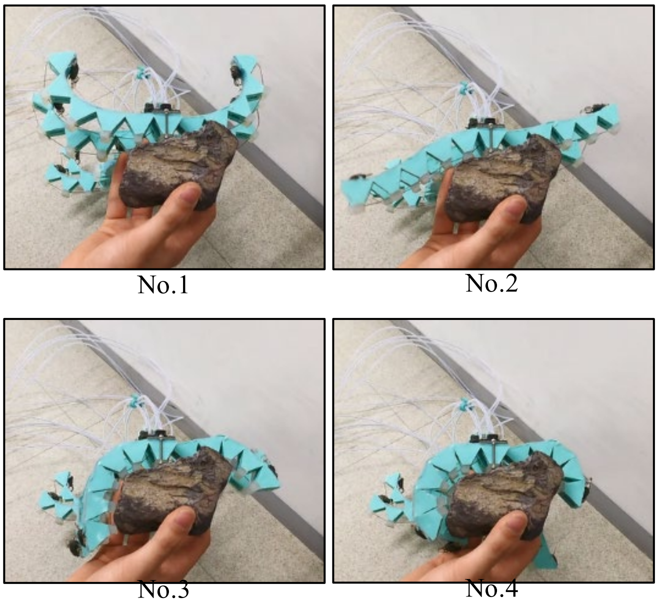

Figure 14 The leg’s motion

4.2. Experiments to confirm trunk mechanism

Figure 15 shows the maximum bending motion of the trunk. From this, we confirmed that the trunk has enough movable range.

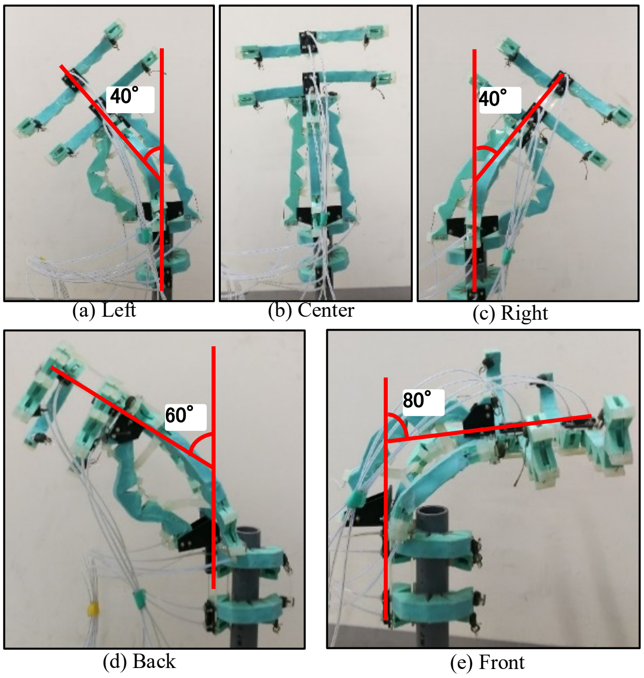

Figure 15 Performance of body parts

4.3. Climbing columnar pipes

To confirm the basic ability of the proposed robot, we conducted experiments using various vinyl chloride pipes of different sizes. Figure 16 shows an example of the realized climbing behaviour and Table 3 lists the results. In these experiments, the sizes of the pipes were unknown and not measured. The friction coefficient between the pipe and the leg was about 0.65.

From these result, we confirmed that the leg could grasp various sized pipes by just pulling the string, and the robot could climb them. However, in case that the diameter was less than 14 mm, there was a gap between the pipe and the leg even though all the joints were closed. Therefore, enough friction was not maintained and the robot could not climb. In contrast, in case that the diameter was over 61 mm, the length of the leg was too short to cover the pie, and enough grasping force did not produced. Therefore, from these results, we confirmed that the proposed robot can climb pipes of various sizes from 8A to 50A.

In addition to just climbing, we confirmed the load capacity. The maximum weight the robot could lift up at 25A pipe was about 1.0 Kg. It is enough to carry the motors and battery. So, in our future work, we will embed these necessary pars into the robot body.

TABLE.3 Experimental results (various pipes)

Pipe's size (diameter)	6A (11 [mm])	8A (14 [mm])	10A (17 [mm])	15A (22 [mm])
Climbed or failed	Failed	Climbed	Climbed	Climbed
Pipe's size (diameter)	20A (27 [mm])	25A (34 [mm])	32A (43 [mm])	40A (49 [mm])
Climbed or failed	Climbed	Climbed	Climbed	Climbed
Pipe's size (diameter)	50A (61 [mm])	65A (76 [mm])		
Climbed or failed	Climbed	Failed		

4.4. Climbing various columnar objects

To confirm adaptability to various objects, we employ connected columnar pipes, square pipes, long balloons, and natural trees.

Figure 17 shows a result of connected columnar pipes (18 mm and 22 mm). These pipes are not parallel and the distance between them changes while climbing. Nevertheless, the robot could climb using the same preprogramed pattern.

Figure 18 shows the result of using a square pipe (30 mm × 30 mm). Here as well, the robot could climb the square pipe without changing its locomotion pattern; the legs passively adapted to the square shape.

Figure 19 shows the result of using a long balloon connected to a columnar pipe. In this case, the right legs have to grasp the rigid pipe and left legs have to grasp the soft balloon. Nevertheless, the robot could climb it using the same locomotion pattern.

From these results, we confirmed that the proposed mechanism perfectly works, and the robot could climb various unknown columnar objects by utilising the soft body. In addition, it required no sensor to measure the shape of the columnar objects, and the calculation cost to control body was very low in spite of its many degrees of the freedom. These adaptive behaviour was realised by the interaction between the soft body and the environment.

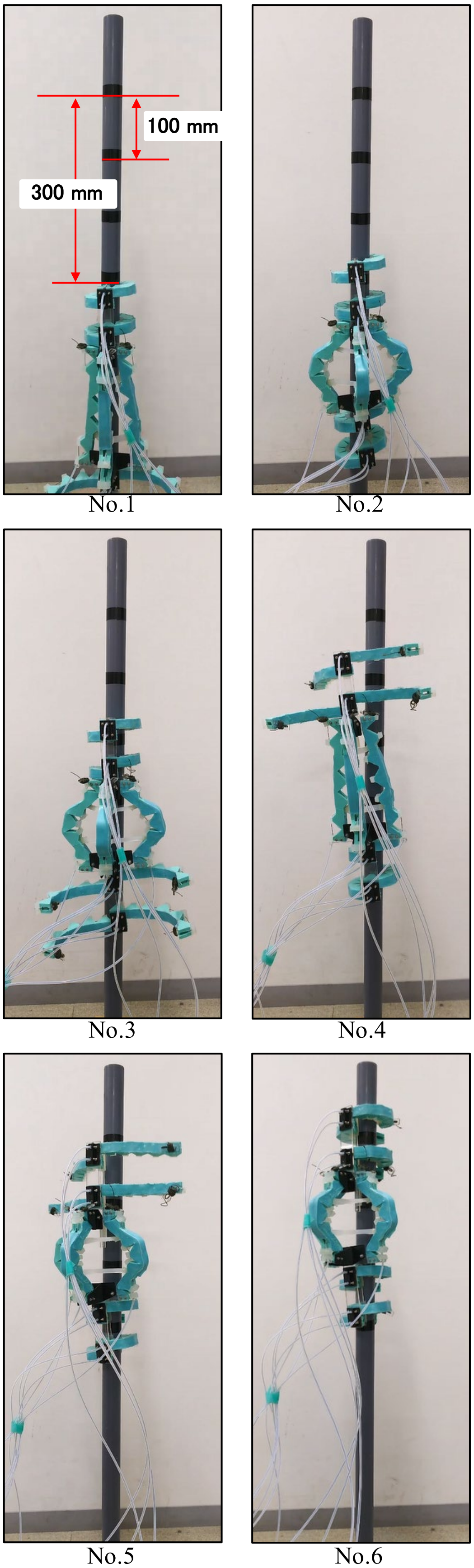

Figure 16 Experimental result (column pipe d = 34 mm)

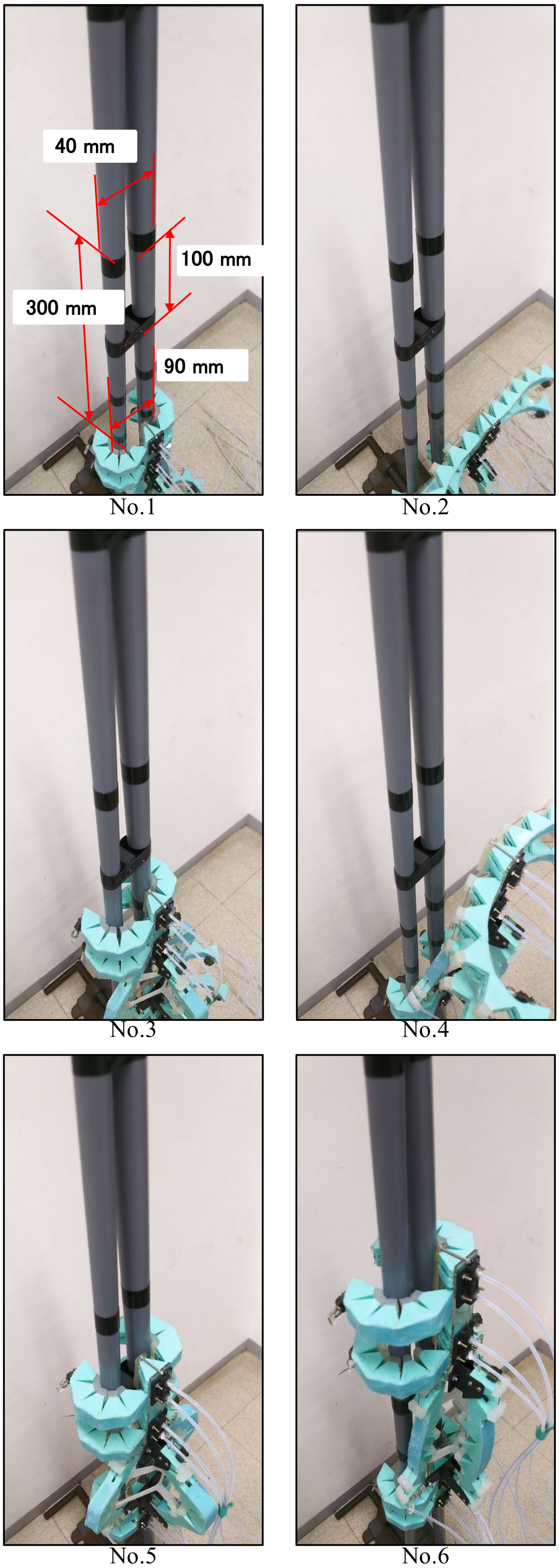

Figure 17 Experimental result (two pipes)

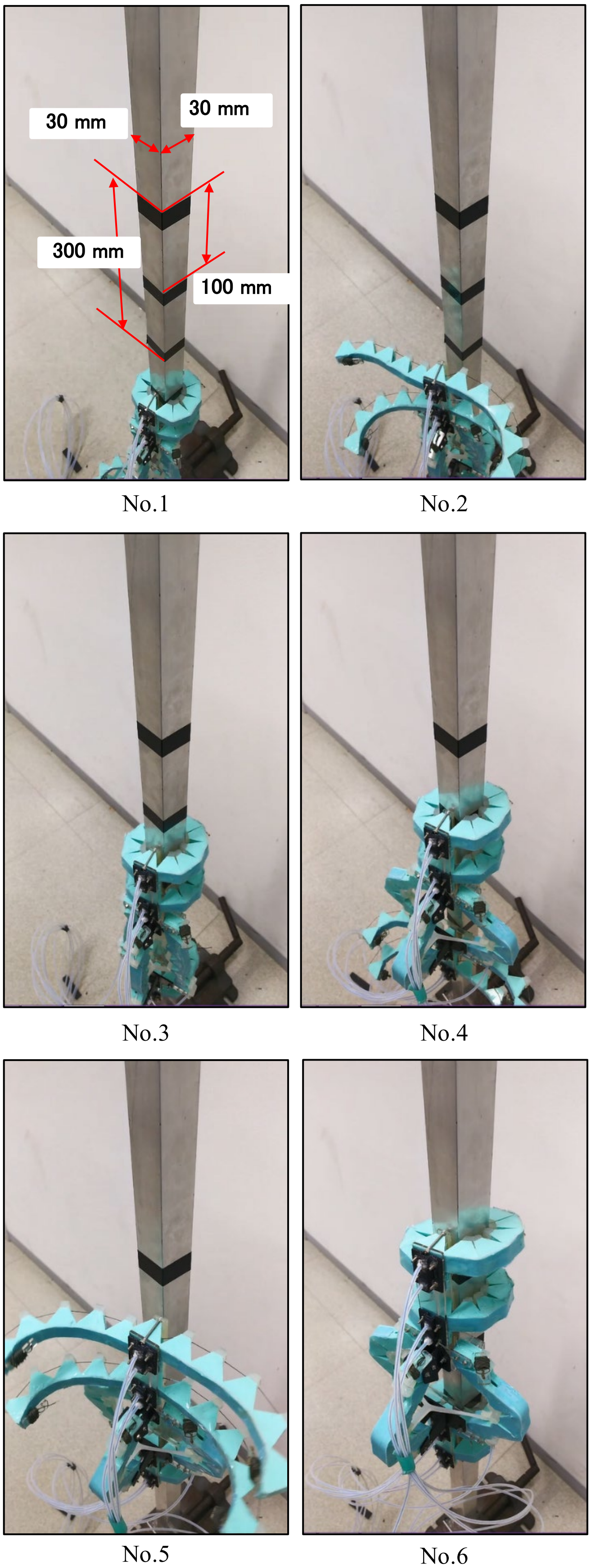

Figure 18 Experimental result (square pipe)

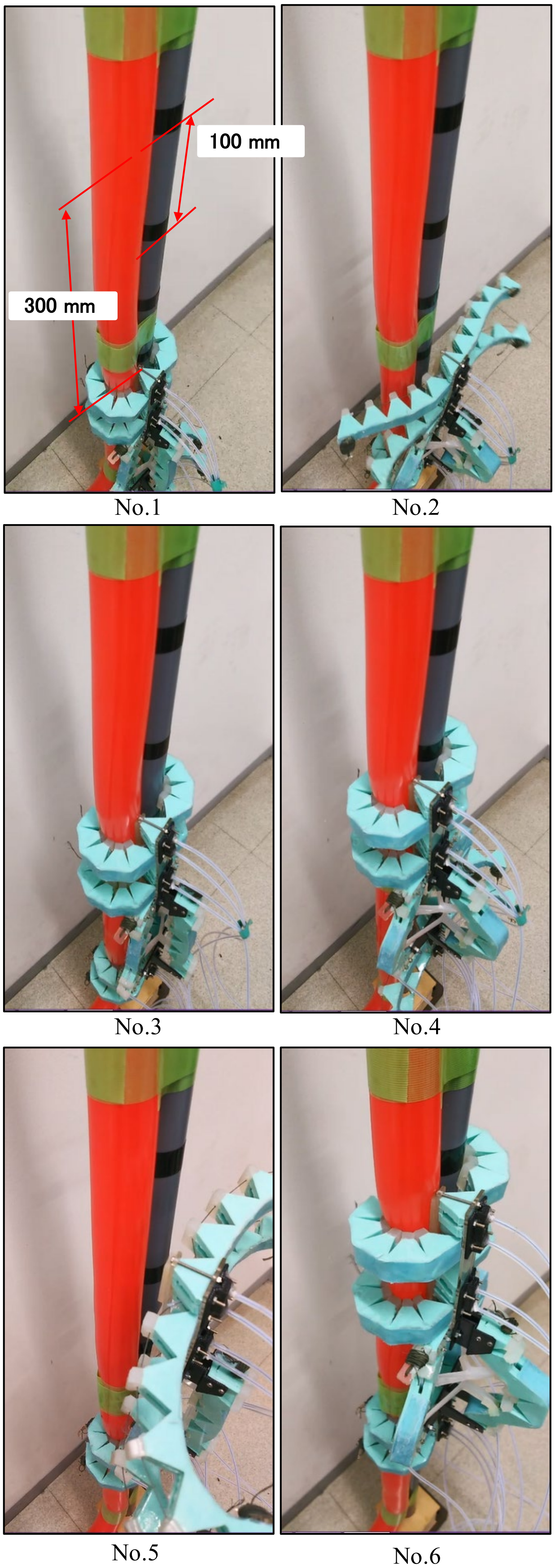

Figure 19 Experimental result (balloon and pipe)

Next, we confirm the ability using manual control. In the proposed mechanism, the micro-behaviour to adapt to the differences of the columnar objects are passively realised by the soft body, so just by using several switches, we can control the robot. Fig. 20 shows the Graphical User Interface. By using this user interface, we can control macro-behaviour which means moving direction of the robot.

Figure 21 and 22 shows the result of using a natural tree. In these cases, the robot had to be controlled by a human operator using Graphical User Interface as shown in Fig. 22. We confirmed that by controlling the trunk to desired three-dimensional direction, the robot could climb complex unknown objects such as a tree.

Fig. 20 User interface for manual control

No.1

No.2

No.3

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No.6

Figure 21 Experimental result (Natural tree)

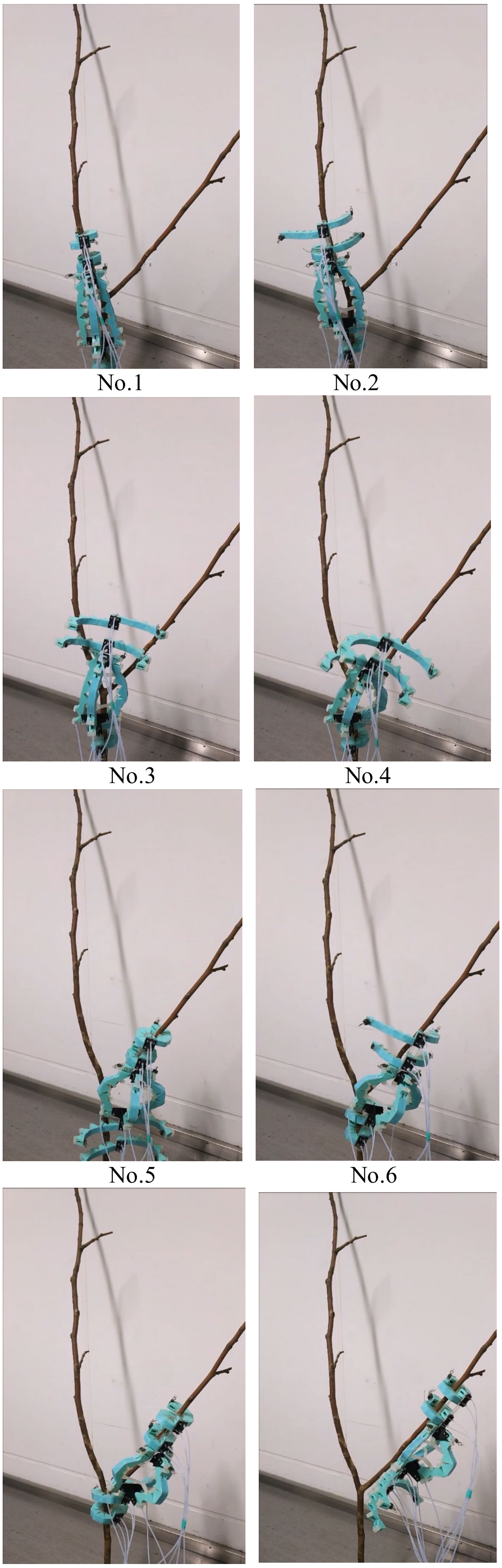

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Figure 22 Experimental result (Natural tree branches)

5. Conclusion

In this paper, we proposed a new simple mechanism to realize octopus-like grasping behaviour, and by applying this mechanism to a climbing robot, we realized a soft robot that can climb various columnar-shaped objects. The behaviour of the robot is realized using dynamics of the soft body. Thus, calculations on a CPU to control its many degrees of freedom are not required. By only repeating a simple pattern, it could climb unknown objects without sensing its shape. Experiments using pipes, long balloons, and natural trees were conducted, and we demonstrated the effectiveness of the proposed robot.

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